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BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

SUBJECT: Trip Report: AAP Software Review at MIT, June 10, 11, 12, 1969 - Case 610

DATE: July 2, 1969

FROM: D. A. De Graaf
C. O. Guffee
K. E. Martersteck

ABSTRACT

A review of AAP software requirements for the CMC and LGC was held at MIT on June 10, 11 and 12 at which time MIT presented functional descriptions of the software and simulation results. The more significant conclusions were:

1. The CSM DAP will control all four AAP configurations; will operate in the free, attitude hold, or automatic mode; and allow the choice of torque couple or translation jet control for pitch and yaw in the cluster configurations. Jet select logic will compensate for announced jet failures and tolerate at least one unannounced failure. No automatic detection and diagnosis of jet failures will be implemented - astronauts are present.

2. MIT favors use of modified LM ascent guidance equations for the SPS insertion because of the similarity of the LM equations with the launch vehicle IGM guidance. However, Hohmann guidance which is currently baselined has not been ruled out by MIT.

3. During OWS orbit circularization by the CSM, acceleration is so low that PIPA quantization and bias present special problems. A modified external-Δv steering law performs well. Special jet inhibition logic in the DAP minimizes bending mode excitation.

4. The LGC DAP is being designed to control the LM/ATM alone only. MIT will study means for deactivation quickly after docking. Sophisticated automatic detection and isolation of jet failures will be included.

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5. Rendezvous radar acquisition and lock-on is assured, even without ground update, based on the nominal LM/ATM and OWS state vectors loaded before launch. Sidelobe lock-on is entirely acceptable because angle bias errors are accurately estimated by the navigation equations.

6. MIT station keeping simulations indicate that the LM can successfully navigate at reasonable distances (200 to 800 ft). At these ranges station keeping will require 15 ft/sec for a LM position above the OWS and 7 ft/sec if the LM is ahead of the OWS.

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MEMORANDUM FOR FILE

Introduction

Beginning June 10, MIT/IL presented a 2-1/2 day review of their current status in developing software for AAP. Attendees were from MSC, North American Rockwell, TRW, McDonnell Douglas, Grumman, and Bellcomm. The authors represented Bellcomm.

The presentations dealt with the functional requirements that must be implemented in the Command Module Computer (CMC) and the LM Guidance Computer (LGC). The coverage was thorough and included considerable detail, indicating that MIT has been able to redeploy significant effort from Apollo to AAP. While this meeting was loosely called a Preliminary Design Review, it was in fact an informal presentation and discussion. A few questions were identified for future resolution. MIT intends to continue the definition of functional requirements and to have a pre-coding design completed by the end of August 1969.

Changes to the current CMC and LGC programs were identified and described. The AAP versions were dubbed COMMUTER and SOLARSPY in place of COLOSSUS and LUMINARY. A meeting agenda is attached and handouts for each presentation are available from the authors.

CSM Mission Operations Planning

The AAP CMC programs and routines will differ from Apollo generally as follows:

1. All programs and routines required for guidance and navigation only for a lunar mission will be deleted.

2. Routines required for AAP missions such as SPS insertion to orbit, OWS/CSM orbit circularization, and gravity-gradient orientation calculations will be added.

3. The CMC must be capable of calculating the CSM rendezvous with the OWS as well as providing solutions for the LM/ATM rendezvous as a backup. The programs required may differ somewhat from the current Apollo collection.

CSM Digital Autopilot (DAP) Design Specifications

The DAP will be capable of providing altitude control for four AAP configurations:

I. CSM alone

II. CSM/LM-ATM (decoupled mission)

III. CSM/OWS

IV. CSM/OWS/LM-ATM

The DAP will have three modes of operation and will have parameters to allow it to function properly for each of the four AAP configurations. The mode of operation is selected by a switch from among three possibilities:

1. Free Mode - the DAP will not provide attitude control. Rotation hand controller (RHC) and translation hand controller (THC) inputs will be treated as direct acceleration commands. Minimum impulse torques are also available.

2. Attitude Hold Mode - the DAP will hold inertial attitude and respond to manual commands via the hand controllers.

3. Automatic Mode - the DAP will provide attitude control as directed by guidance routines; however, manual attitude rate commands will override automatic commands.

In all modes, translation commands will be combined with rotation commands so as to produce the translational forces; however, attitude control commands will have priority over translational commands. In Configurations II, III, and IV, Y and Z translation is difficult if not impossible due to the offset cg location. There may be no response to Y or Z THC inputs, but this is not yet firmly established.

The DAP will continue to function "efficiently" with an off failure of any single jet or quad provided this information is manually inserted via the DSKY. MIT accepts the design requirement to maintain attitude control in the face of one jet failed on. No automatic jet failure detection logic, on or off, will be included; the astronauts can perform that function.

Either torque couples or Y-Z translation jets may be manually selected for pitch and yaw control in Configurations II, III, and IV. However, if the chosen mode is rendered ineffective by failed jets, the logic automatically reverts to the other mode.

Modification of the Apollo CSM DAP for AAP

The DAP computations are repeated every 0.1 sec and consist of three main sections: the state estimator, the phase plane logic, and the jet select logic.

The state estimator is a recursive filter operating on gimbal angle readings to estimate body angle, rate, and acceleration. This sophisticated approach is needed to filter out effects of vibration and angle quantization. The filter accounts for expected angular acceleration for commanded jet firings. For AAP, acceleration will be estimated in addition to angle and angle rate and the smoothing time will be appropriately increased. An output value different from zero will be a measure of unmodeled angular acceleration such as gravity gradient, aerodynamic, or unknown failed jet torques.

Input angle data to the filter will be tested against a threshold and the filter will respond only when the measurements deviate significantly from the value predicted in the model. This non-linearity will tend to make the filter insensitive to oscillatory input data due to vehicle bending modes and make the state estimate correspond to the average state of the entire cluster, rather than to local conditions within the CM.

The phase plane logic uses current values from the state estimator of angle and angle rate to decide whether jet firings are required. This logic for AAP will be essentially the same as for Apollo. A modification to the shape of the switching lines may be necessary if the dead band is reduced from ± 0.5 degrees to ± 0.2 degrees. However, the same general shape will be used for all four AAP configurations with different parameter values used to account for the different dynamic responses.

Jet select logic for AAP is considerably more complicated than Apollo due to the four configurations and the choice of torque couple or Y,Z translation for pitch and yaw control. As previously mentioned, the system will tolerate certain unknown jet failures and operate with slight degradation when failures are identified. A new feature will be logic to inhibit jet firing about an axis for a time (perhaps 10 sec) after the previous control action about that axis. The time will be chosen to preclude exitation of all known resonances by cyclic jet firing.

Control Interaction During Orbit Circularization

During RCS thrusting to circularize the CSM/OWS orbit, steering control presents special design problems due to the low acceleration, PIPA quantization and bias, and low structural tolerance to bending forces. MIT investigated several approaches to steering control. The simplest is not to steer at all in a closed-loop sense, but merely to align the body axis in the pre-burn Δv direction. This would result in an expected crosswise velocity error at cutoff of 1.3 ft/sec if the attitude wandered randomly within the ± 0.5 deg deadband, or 5.3 ft/sec if disturbance torques acted to produce a limit cycle 5° off center, or 3.8 ft/sec in the event of a failure of one of the four jets. It was noted that the +X jets are canted out 10° and it happens that this puts the line of thrust just through the cg. Thus, a jet failure won't induce any significant unbalanced torque but it will significantly change the effective direction of acceleration. MIT plans no detection logic for this type of failure either, choosing to rely on external monitoring.

The no-steering error can be reduced to 0.1 ft/sec by closing the loop, but special modifications to the cross-product steering calculation are needed to guard against quantization problems. Some early simulations were shown in which PIPA quantization interacted with the steering loop to cause very erratic steering. MIT recommends closed loop steering with appropriate fixes.

G&N for CSM/OWS Orbit Circularization

Three guidance schemes have been considered for the orbit circularization maneuver - Hohmann, P. E., and external-Δv. The study included effects of IMU errors, ignition delays, and RCS jet failures.

MIT concluded that Hohmann and P. E. guidance are less effective than external-Δv guidance in circularizing the CSM/OWS. Also external-Δv guidance is less sensitive to ignition time delays and has a more desirable rate command history. However, it is proposed that X-axis steering be substituted for cross-product steering in order to reduce the cross-axis errors resulting from PIPA bias and quantization noise.

CSM G&N for the SPS Insertion Technique

MIT has studied possible guidance schemes for the AAP SPS insertion including Hohmann guidance, semi-latus rectum/eccentricity guidance (P. E.), and LM ascent guidance. The LM ascent guidance equations can be shown to be equivalent to the iterative guidance mode (IGM) equations used by MSFC in the launch vehicle. MIT prefers the LM ascent equations over the IGM equations because the LM equations are simpler and have already been programmed by MIT for the LGC.

MIT has rejected P. E. guidance because it can result in large differences in pitch angle between the vehicle attitude at S-IVB cutoff and initial required CSM attitude at SPS ignition. Further, P. E. guidance fails to obtain satisfactory apogee and perigee altitudes when there are IMU and navigation errors.

Hohmann guidance is able to obtain a satisfactory orbit with off-nominal conditions and system errors. MIT has not completed off-nominal tests with the LM ascent equations; however, MIT feels that they will out perform the Hohmann guidance equations. Further test results will be obtained before making a final decision.

CSM-OWS Rendezvous/LM-ATM-OWS Rendezvous

Navigational studies have been performed for the CSM rendezvous with the OWS assuming ground-targeted rendezvous phasing maneuvers (NCC and NSR) and on-board targeting from TPI through second midcourse correction - followed by manual braking. It was assumed that the CSM received a ground update of its state prior to initialization of the rendezvous sequence and that on-board navigation was used throughout the rendezvous.

Simulations show that the CSM can satisfactorily rendezvous with the OWS when navigation is performed with either VHF ranging and sextant, VHF ranging alone, or sextant alone. Not surprisingly, the smallest navigation errors and consequently smallest Δv expenditure is obtained when using both sextant and VHF ranging.

A study of CSM monitor of LM-ATM rendezvous was also conducted. The study used VHF ranging beginning at LM insertion and both VHF ranging and sextant tracking from NSR through the second midcourse. MIT concluded that the CSM navigation system can provide excellent backup for the LM in case of rendezvous radar failure.

Modifications to LM DAP for AAP

The LM DAP will have an unmodeled angular acceleration estimator for all three spacecraft control axis running continuously, instead of estimators about Q and R only during powered flight. The estimator will be used to improve the DAP performance when disturbing angular accelerations exist and also will aid in the detection of certain types of jet failure. Expected torques due to jet firings, including Y-Z translation firings will be explicitly modeled. The difference in torque between +X jets with plume deflectors and -X jets without deflectors will be accounted for.

The phase plane logic will be essentially the same as in Apollo with some simplifications. The phase plane is divided into two sectors: ROUGHLAW used when errors exceed 11.25 deg or 5.625 deg/sec, and FINELAW when they don't. No special phase plane is needed for translation burns because the thrust is so low. The deadband will be $\pm 1.$ degree.

The Apollo DAP jet select logic must be modified to eliminate 4-jet simultaneous Y-Z translation and to eliminate 2-jet P-axis rotations using jets in adjacent quads. Both of these changes are to prevent loss of attitude control for the AAP LM. In addition, the jet select logic will give attitude control priority over translational control.

The manual attitude rate command link will be able to command a single value of angular rate from the LM DAP. There will be independent channels for rate commands about the separate LM axes. The rate that will be commanded will be stored in erasable memory and will be between 0.5 and 2 deg/sec (the exact value will be determined later).

The DAP will be able to automatically avoid attitude maneuvers which will result in IMU gimbal lock.

Automatic jet failure detection logic will be included in the LM DAP, unlike the CM, since there are no men present. Failure detection will be based on excessive unmodeled angular acceleration coming out of the state estimator. Any on failure or an off failure of a frequently used jet will be detectable. After detection, the program enters a diagnostic phase to isolate the failure. First, all jet firings are suspended to look for an on failure. If this test is negative, test firings are made of suspected off failed jets. When the failure is isolated, the propellant supply valve is closed, the good jet of the pair is fired to relieve line pressure, marker bits are set in core, and normal operation is resumed. All this can take up to eight seconds and the propriety of entering the diagnostic phase during critical regimes of the flight is still an open question. MIT doesn't feel that any of the main burns in the rendezvous profile would be significantly degraded by an eight-second interruption, and station keeping wouldn't be critical either, but the docking operation probably wouldn't tolerate a suspension of control. The emergency -X translation switch would still work during the diagnostic suspense because that signal bypasses the computer and goes directly to the secondary solenoids, but if the computer had previously shut the supply valves to one of those four jets, that jet wouldn't fire. If the ground controllers think they know better, they can reset the failure marker bits and restore full operation, but they can't inhibit the failure detection logic from detecting the same failure again.

All translational maneuvers through TPI will be made with the $\pm$X axis jets. Only two of the four jets will be used at a time; the DAP will switch periodically between pairs provided none are failed.

<u>LM DAP Design Integration and Requirements</u>

The DAP is being designed to provide attitude control and translational capability for the LM-ATM vehicle only. The autopilot control modes are:

1. Automatic/Attitude Hold Mode - the DAP will hold attitude angles and rates as commanded by the guidance program and will respond to its translation commands also.

2. Manual/Local Vertical Mode - the DAP will hold an attitude with respect to the local vertical. The guidance program will have a memory in the form of a direction cosine matrix which relates body axes to local vertical axes. Upon entering this mode, the DAP will track the proper attitude. Upon receipt of manual rate commands, the DAP will perfrom the rotational maneuver as long as the command is present. Upon termination of the manual command, the directional cosine matrix will be updated and the DAP will continue to hold its new attitude with respect to the local vertical.

3. Line-of-Sight (LOS) Mode - the DAP will align the LM +X-axis to continually point along the line-of-sight to the OWS. This mode would be used for manual control of terminal phase braking as well as TPI. As in the local vertical mode, RHC inputs would cause an additive body axis rotation rate. On termination, the new orientation would be maintained with respect to the line-of-sight.

4. Free Mode - the DAP will be in an off mode and will ignore all translational and rotational commands. The Free Mode will be required immediately upon docking with the OWS in order to prevent the LM DAP from opposing the OWS/CSM attitude control system.

Suitable initialization of each of these modes remains an open question, as MIT had not been advised of operational requirements. One reasonable possibility that was discussed is to begin inertial hold at whatever orientation the vehicle has, but on initiating local vertical or line-of-sight hold, to rotate immediately to place the X axis along the respective reference direction.

Rendezvous Radar

MIT studies show that rendezvous radar (RR) main lobe lock-on to the OWS after insertion is assured. This assumes that pointing directions are calculated from pre-launch nominal state vectors for OWS and LM/ATM. Pointing errors due to actual launch dispersions and platform misalignment at 10 min after insertion total only 0.57 deg, 3σ, well within the 2.83 deg required for 99.74% probability of achieving main lobe lock-on.

Even if some anomalous situation were to cause a side lobe lock-on, no harm would be done. The navigation filters will be used to estimate angle biases along with position and velocity and simulations show rapid convergence to the correct value of about six degrees. Any error in the state vector is thereby nullified; moreover, if RR lock is intentionally broken and subsequently resumed, main lobe reacquisition is assured.

After TPI, the navigation system will stop estimating RR angle biases and begin estimating RR range and range rate biases. Preliminary studies indicate that the RR can function properly at the distances required for station keeping.

There is a possibility that RR track will be broken if the LM approaches to within 130 feet of the OWS. If this happens, the LM must increase the separation distance beyond this threshold and initiate RR reacquisition. Further studies are required to assess the effects of a sidelobe lock-on at these close ranges.

DAP Deactivation

The problem of what happens if the LM DAP is active after docking with the OWS (or CSM) has not yet been studied, nor has an acceptable method of immediately deactivating the

LM DAP been determined. The LM DAP is not being designed to control the attitude of a docked configuration. After the design of the LM DAP has been completed, MIT will study how the DAP will react when the LM is in a docked configuration with an active CSM/OWS control system. This study will reveal any potential dangers due to an active LM DAP. The problem of freeing the LM DAP is also to be studied.

LM/ATM Rendezvous

The baseline for AAP-4 rendezvous is ground control up to TPI and onboard automatic control of TPI, braking, and station keeping with manual backup for the automatic control portion. MIT has performed the following navigation studies.

1. Ground controlled NCC/NSR coelliptic maneuvers with automatic control of TPI and midcourse corrections. This study was performed for both MSFN update of the LM state and for total onboard navigation of the LM state.

2. Total onboard targeting of rendezvous after insertion for stable orbit rendezvous (SOR), for present Apollo concentric flight plan (CFP), and for a possible onboard version of the NCC/NSR targeting routine.

3. Automatic terminal phase braking (TPF) for both Lambert targeting gates, and automatic LOS braking.

The general conclusion is that the guidance and navigation system can obtain satisfactory terminal conditions for station keeping regardless of the selected mode of rendezvous. As usual there are advantages and disadvantages for each of the possible control modes, and the final choice must be based on information gained from further simulations.

Station Keeping

MIT proposed an automatic station keeping routine in which the LM is kept in a position limit cycle with respect to the MDA window. The guidance and navigation is based upon relative position and velocity of the LM with respect to the OWS with calculations being performed in a local vertical coordinate system centered in the OWS. Maneuver corrections would be required to keep the LM within its limit cycle as well as to insure that the LM does not exceed the window viewing limits of 60° and distance limits to OWS of 700 to 800 feet.

Simulation results indicate that the proposed station keeping guidance and navigation system will operate correctly and very efficiently. The station keeping corrections are expected to be about 15 ft/sec for station keeping above the OWS and about 7 ft/sec for station keeping in front of the OWS.

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AGENDA FOR AAP PRELIMINARY DESIGN REVIEW

MIT Instrumentation Laboratory*

June 10, 11, 12, 1969

Tuesday, June 10: CSM Programs

8:30 - 9:15 a.m.	CSM Mission Operations Planning; AAP CSM Program List; PDR Presentation Plans...G. Stubbs, R. Werner
9:15 - 11:30 a.m.	Modifications of the Apollo CSM DAP for AAP: (1) State Estimator... E. Jones (2) RCS Control Laws...J. Turnbull (3) Jet Select Logic...J. Turnbull (4) Jet-inhibition Solution to Vehicle Bending Problem...G. Kalan (5) Low-thrust Guidance and Control Interaction... A. Penchuk
11:30 - 12:00 Noon	CSM DAP Design Integration...J. Turnbull
12:00 - 1:00 p.m.	LUNCH
1:00 - 2:00 p.m.	Assumed Design Specifications for the CSM DAP... J. Turnbull
2:30 - 3:30 p.m.	CSM G&N for "2-1/2 Stages to Orbit"...P. Philliou
3:30 - 3:45 p.m.	CSM-OWS Rendezvous...E. Muller, P. Kachmar
3:45 - 4:15 p.m.	G&N for CSM-OWS Orbit Circularization...P. Plender
4:15 - 5:00 p.m.	Discussion of PDR Conclusions and Action Items... G. Stubbs.

*All meetings to be held in the Second Floor Classroom.

AGENDA FOR AAP PRELIMINARY DESIGN REVIEW

MIT Instrumentation Laboratory*

June 10, 11, 12, 1969

<u>Wednesday, June 11: LM/ATM Programs</u>

8:30 - 9:15 a.m.	LM/ATM Mission Operations Planning, Program List, PDR Presentation Plans... G. Stubbs, R. Werner
9:15 - 11:30 a.m.	Modifications of the LM DAP for AAP (1) State Estimator... R. Rose a. Disturbance Acceleration Estimator b. Trap Size (2) RCS Control Laws... R. Rose (3) RCS Control Authority Computation... G. Kalan (4) Jet Selection Logic... G. Kalan a. Prevention of Attitude Loss during Translation b. Jet Inhibition during Docking (5) Manual Modes... G. Kalan (6) Gimbal Lock Avoidance in Manual Modes... G. Kalan (7) Jet Failure Detection... R. Rose
11:30 - 12:15 p.m.	LM/ATM DAP Design Integration... G. Kalan
12:15 - 1:15 p.m.	LUNCH
1:15 - 2:15 p.m.	Assumed LM/ATM DAP Requirements... G. Kalan
2:15 - 2:45 p.m.	Guidance-Autopilot Interface; Gimbal Lock Avoidance... A. Klumpp
2:45 - 3:15 p.m.	Prelaunch and Boost... R. White
3:15 - 4:15 p.m.	Rendezvous Radar... L. B. Johnson (1) Rendezvous (2) Station Keeping
4:15 - 5:15 p.m.	LM/ATM Rendezvous... E. Muller, P. Kachmar

*All meetings to be held in the Second Floor Classroom.

AGENDA FOR AAP PRELIMINARY DESIGN REVIEW

MIT Instrumentation Laboratory*

June 10, 11, 12, 1969

Thursday, June 12: LM/ATM Programs, cont'd.

8:30 - 9:00 a.m.	LM/ATM RCS Thrusting for Rendezvous Maneuvers... Chung Pu
9:00 - 10:30 a.m.	Station Keeping...D. Gustafson
10:30 - 10:40 a.m.	Local Vertical Steering...Chung Pu
10:40 - 11:00 a.m.	Conics and Integration...W. Robertson
11:00 - 11:30 a.m.	Interfaces: Operational and Hardware...R. Werner
11:30 - 12:30 p.m.	Discussion of PDR Conclusions and Action Items... G. Stubbs.

*All meetings to be held in the Second Floor Classroom.